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A model for the investigation of the microclimate of canopies - I: Description, and some results for a dry, and a completely wet, canopy.

by N Thompson

1. Introduction The duration of leaf wetness in cereal canopies following rain or the formation of dew is of importance in the development of fungal diseases of the plants. The rate of field drying of hay while affected by dew or rainfall also depends in a complex way on the micrometeorology of the swath. Problems such as these are not really suitable for attack by a method using the combination formula because the drying process takes placeat different rates at different heights within the crop or swath. An approach which recognises and quantifies this variation with height is outlined in this memorandum: it is based to a large extent on canopy models by Waggoner and Reifsnyder (1968), Waggoner et al (1969), and Goudriaan and Waggoner (1972).

2. The basic model The foliage of the plant canopy is visualized as being concentrated at the mid-levels of $n-1$ layers, each of thickness $h/(n-1)$ where h is the overall height of the canopy (Figure 1). The processes within the canopy are driven by net radiation $RADN(o)$ at the top of the canopy, by wind speed $(U(z))$, temperature $(T(z))$ and specific humidity $(q(z))$ at a height z, and by a heat flux (G) into the soil: these external variables are assumed to be known. A sensible heat flux H_i leaves the ith layer and encounters first a leaf (laminar) boundary layer resistenace r_i and then a turbulent resistance R_i before reaching the (i-1)th layer of foliage above. The flux is driven by a potential P_i. Similarly the water vapour flux E_i from the ith layer, which is driven by a potential $\mathcal{E}_i$, encounters a layer stomatal resistance r_{si}, boundary layer resistance r_i and turbulent resistance R_i before it reaches the next layer above. Heat storage within each layer, and energy used in photosynthesis are assumed negligable and so the radiation absorbed by a layer is equal to the sum of the sensible and latent heat fluxes leaving it. At the soil surface the sensible heat flux from the soil (H_n) is controlled by the laminar boundary layer resistance of the soil surface (r_n) rather than a leaf boundary layer resistance before entering the turbulent air above. The water vapour flux from the surface is assumed to encounter a surface resistance r_{sn} (akin to a stomatal resistance) before reaching the surface laminar boundary layer above.

3. Model details

3.1 Radiation Net radiation at the canopy top is given by (Monteith and Szeicz 1961)

$$RADN(o) = \frac{(1-\alpha)}{(1+\beta)} S F_1 \sin\Theta + L_o F_2 \qquad (1)$$

where α = short-wave albedo ($\simeq 0.25$ for green crops).

β = heating coefficient ($\simeq 0.15$ for crops of medium height not under water stress, $\simeq 0.2$-0.3 for grass under stress, or for drying hay).

Θ = solar elevation.

S = solar constant.

F_1 = transmitted fraction of short-wave radiation.

F_2 = transmitted fraction of long-wave radiation.

L_o = a long-wave radiation term ($\simeq -60$ Wm^{-2} by day
$\simeq -70$ Wm^{-2} by night).

F_1 and F_2 are related to amount (fraction) of low, medium and high cloud by (Gadd and Keers 1970)

$$F_1 = (0.6+0.2\sin\theta)(1-m_l C_l)(1-m_m C_m)(1-m_h C_h) \quad (2)$$

$$F_2 = (1-n_l C_l - n_m C_m - n_h C_h) \quad (3)$$

where $m_l = 0.7$, $m_m = 0.7$, $m_h = 0.4$,

$n_l = 0.6$, $n_m = 0.3$, $n_h = 0.1$.

Solar elevation is given by

$$\sin\theta = \sin\delta \sin\phi - \cos\delta \cos\phi \cos(\pi t/12) \quad (4)$$

where t = local time in hours.

ϕ = latitude.

$$\delta = 0.41 \cos\left(\frac{2\pi(d-172)}{365}\right) \quad (5)$$

d = day of year ($1 \equiv$ 1 January)

Hughes et al (1977) give the annual variation of the solar constant as

$$S = 1360(1 + 0.0335 \cos(2\pi d/365)) \quad (Wm^{-2}) \quad (6)$$

Eq (2) was derived in part by Lumb (1964) using weather ship data, and overestimates F_1 in more turbid atmospheres: a more satisfactory expression for general use over land is probably

$$F_1 = 0.85(0.6 + 0.2\sin\theta)(\cdots)(\cdots)(\cdots) \quad (7)$$

: this is used in the model.

Following Denmead (1976) the net radiation within the canopy is assumed to decrease exponentially with increasing leaf area index (LAI): LAI in this case is accumulated from the top of the canopy downwards so that Σ LAI (i) is the leaf area index between canopy top, and bottom of the ith layer (the leaf area index LAI (i) within a layer is defined as the area of leaves within the layer per unit horizontal area, taking only one side of each leaf into account). Thus the net radiation at the bottom of the ith layer is given by

$$RADN(i) = RADN(o) \exp\left(-k' \sum_{p=1}^{i} LAI(p)\right) \quad (8)$$

The extinction coefficient (k') varies with type of crop and with solar elevation. For cereals the following relations are assumed:

(a) daytime

$$k' = 0.2\left(1 + 3/(1+2\theta/\pi)\right) \quad (9)$$

(b) nighttime

$$k' = 0.7 \qquad (10)$$

Extinction coefficients for other crops are not well known, though Monteith (1973) gives some values for solar radiation (for which according to Denmead k' is somewhat smaller than for net radiation) ranging from 1.1 for clover to 0.4 or less for ryegrass. In the absence of more specific data for net radiation the relations (9) and (10) are assumed to apply to all canopies treated by the model.

3.2 Leaf area index The distribution of leaves within canopies varies widely with the type of plant involved. However a satisfactory approximation for many crops grown above a nearly weed-free surface is that foliage is distributed normally about a height $h/2$ with a standard deviation σ. If the leaf area density (LAD), defined as the leaf area index per unit height, is introduced, then

$$LAD(z) = LAD(h/2)\exp\left(-\tfrac{1}{2}\cdot\left(\frac{h/2-z}{\sigma}\right)^2\right) \qquad (11)$$

where z = height above ground

Thus

$$LAI(i) = \int_{h(n-i)/(n-1)}^{h(n-i-1)/(n-1)} LAD(z)\,dz$$

$$\simeq LAD(h/2).h\left[\exp\left(-\tfrac{1}{2}\cdot\left(\frac{h}{\sigma}\left(\frac{i}{n-1}-0.5\right)\right)^2\right)\right.$$

$$\left.+\exp\left(-\tfrac{1}{2}\cdot\left(\frac{h}{\sigma}\left(\frac{i-1}{n-1}-0.5\right)\right)^2\right)\right]/2(n-1) \qquad (12)$$

For cereals above a weed free surface, where the foliage tends to be concentrated at a height above the ground greater than half the height of the crop, a normal distribution of leaf area density will still be assumed but distributed around a height $3h/4$, so that

$$LAI(i) \simeq LAD(3h/4).h\left[\exp\left(-\tfrac{1}{2}\cdot\left(\frac{h}{\sigma}\left(\frac{i}{n-1}-0.25\right)\right)^2\right)\right.$$

$$\left.+\exp\left(-\tfrac{1}{2}\cdot\left(\frac{h}{\sigma}\left(\frac{i-1}{n-1}-0.25\right)\right)^2\right)\right]/2(n-1) \qquad (12a)$$

3.3 Heat balance of each layer The set of n equations is

$$\left.\begin{aligned} RADN(0)-RADN(1) &= H_1+\lambda E_1 \\ &\vdots \\ RADN(i-1)-RADN(i) &= H_i+\lambda E_i \\ &\vdots \\ RADN(n-1)-G &= H_n+\lambda E_n \end{aligned}\right\} \qquad (13)$$

where λ = latent heat ($\simeq$ 2465000 J Kg^{-1})

G = downward flux of heat into ground

3.4 Sensible heat fluxes The potential of the ith layer is

$$P_i = \Theta_i \rho c_p \tag{14}$$

where Θ_i is the difference in temperature between leaves in the ith layer and the air just above the canopy top. The resistance equations for the differences of potentials between layers are then

$$\left.\begin{aligned} \rho c_p \Theta_1 &= H_1 r_1 + R_1 \sum_{p=1}^{n} H_p \\ &\vdots \\ \rho c_p (\Theta_i - \Theta_{i-1}) &= H_i r_i + R_i \sum_{p=i}^{n} H_p - H_{i-1} r_{i-1} \\ &\vdots \\ \rho c_p (\Theta_n - \Theta_{n-1}) &= H_n r_n + R_n \sum_{p=n}^{n} H_p - H_{n-1} r_{n-1} \end{aligned}\right\} \tag{15}$$

By adding the equations successively a more convenient set is obtained:

$$\left.\begin{aligned} \rho c_p \Theta_1 &= H_1 r_1 + R_1 \sum_{p=1}^{n} H_p \\ &\vdots \\ \rho c_p \Theta_i &= H_i r_i + R_1 \sum_{p=1}^{n} H_p + \cdots\cdots + R_i \sum_{p=i}^{n} H_p \\ &\vdots \\ \rho c_p \Theta_n &= H_n r_n + R_1 \sum_{p=1}^{n} H_p + \cdots\cdots + R_n \sum_{p=n}^{n} H_p \end{aligned}\right\} \tag{16}$$

These equations become after expansion:

$$\left.\begin{aligned} \rho c_p \Theta_1 &= H_1 (r_1 + R_1) + R_1 H_2 + \cdots\cdots + R_1 H_n \\ \rho c_p \Theta_2 &= H_1 R_1 + H_2 (r_2 + R_1 + R_2) + H_3 (R_1 + R_2) + \cdots + H_n (R_1 + R_2) \\ &\vdots \\ \rho c_p \Theta_i &= H_1 R_1 + H_2 (R_1 + R_2) + \cdots + H_{i-1} (R_1 + \cdots + R_{i-1}) \\ &\quad + H_i (r_i + \sum_{p=1}^{i} R_p) + H_{i+1} \sum_{p=1}^{i} R_p + \cdots + H_n \sum_{p=1}^{i} R_p \\ &\vdots \\ \rho c_p \Theta_n &= H_1 R_1 + \cdots\cdots + H_{n-1} (R_1 + \cdots + R_{n-1}) + H_n (r_n + \sum_{p=1}^{n} R_p) \end{aligned}\right\} \tag{17}$$

3.5 Water vapour fluxes The potential of the ith layer is

$$\mathcal{E}_i = \rho Q_i$$

where Q_i is the difference of specific humidity between that in the leaf stomata and that just above the canopy top. It is assumed that air in the stomata is saturated so that

$$Q_i = q_{sat}(T=T_i) - q(h)$$

$$= q_{sat}(T=T_i) - q_{sat}(T=T(h)) + q_{sat}(T=T(h)) - q(h)$$

$$= \Delta' \Theta_i + \delta q \qquad (19)$$

where $\Delta' = \partial q_{sat}/\partial T$, $T(h)$ = temperature just above canopy, and δq is the specific humidity deficit at this latter height. The layer equations are then

$$\left.\begin{aligned}
\rho(\delta q + \Delta' \Theta_1) &= E_1(r_{s1} + r_1) + R_1 \sum_{p=1}^{n} E_p \\
&\vdots \\
\rho(\delta q + \Delta' \Theta_i) &= E_i(r_{si} + r_i) + R_1 \sum_{p=1}^{n} E_p + \cdots + R_i \sum_{p=i}^{n} E_p \\
&\vdots \\
\rho(\delta q + \Delta' \Theta_n) &= E_n(r_{sn} + r_n) + R_1 \sum_{p=1}^{n} E_p + \cdots + R_n \sum_{p=n}^{n} E_p
\end{aligned}\right\} \qquad (20)$$

Eq (20) may be re-written in the same form as Eq 17 to yield an equivalent set, i.e.

$$\left.\begin{aligned}
&\vdots \\
\rho(\delta q + \Delta' \Theta_i) &= E_1 R_1 + E_2(R_1 + R_2) + \cdots + E_{i-1}(R_1 + \cdots + R_{i-1}) \\
&\quad + E_i\left(r_{si} + r_i + \sum_{p=1}^{i} R_p\right) + E_{i+1} \sum_{p=1}^{i} R_p + \cdots + E_n \sum_{p=1}^{i} R_p \\
&\vdots
\end{aligned}\right\} \qquad (21)$$

3.6 Inter-layer resistances The turbulent diffusion coefficient within canopies shows a roughly exponential decrease with decreasing height during the daytime (e.g. Denmead 1976, Uchijima 1976):

$$K(z) = K(h) \exp(-m(1 - z/h)) \qquad (22)$$

where $K(h)$ is the diffusion coefficient at the top of the canopy. m probably varies with different crops but a constant value of 2.5 will be assumed. The resistance to turbulent transfer between two layers i and i-1 is then

$$R_i = \int_{\frac{h}{n-1}(n-i-0.5)}^{\frac{h}{n-1}(n-i+0.5)} (1/K(z))\, dz$$

$$= \frac{h}{mK(h)}\left[\exp\left(\frac{m}{2(n-1)}(2i-1)\right) - \exp\left(\frac{m}{2(n-1)}(2i-3)\right)\right] \qquad (23)$$

In the case of transfer from the topmost layer to the top of the canopy the expression becomes

$$R_1 = \frac{h}{mK(h)} \left[\exp\left(\frac{m}{2(n-1)} - 1 \right) \right] \qquad (24)$$

Resistance to transfer from the soil surface is discussed later.

At night the profile of resistance may vary markedly from exponential. In particular because the thermal stratification in the lower part of the canopy then favours convection, while a temperature inversion exists in the upper layers, the profiles of resistance often show minima near the middle of the canopy. This complex behaviour is ignored at present in the model, which uses Eq (23) and (24) for both day and night.

3.7 Leaf boundary layer resistance Laminar boundary layers over the leaf surfaces introduce a resistance r which has to be overcome before the property being transferred from the leaf can enter the generally turbulent airflow in the plant canopy. It has been shown that in the case of momentum transfer but ignoring form drag (which does not exist in the case of heat or moisture transfer) the boundary layer resistance of a flat surface of width ℓ exposed tangentially to an airflow U is

$$r_M \simeq 1.5 (\ell/U\nu)^{1/2} \qquad (25)$$

$$= \frac{1.5}{U} (Re)^{1/2} \qquad (26)$$

where ν is the kinematic viscosity (e.g. Monteith 1973). The corresponding resistance for sensible heat transfer is

$$r_H = r_M (\nu/\kappa)^{2/3}$$

$$= 0.80\, r_M$$

$$= \frac{1.2}{U} (Re)^{1/2} \qquad (27)$$

where κ is the thermal diffusivity. The relation for water vapour transfer is

$$r_v = r_M (\nu/D)^{2/3}$$

$$= 0.74\, r_M$$

$$\simeq \frac{1.1}{U} (Re)^{1/2} \qquad (28)$$

where D is the molecular diffusivity. Monteith (1973) suggests that the resistances for leaves may be somewhat less (by 20-30%) than those given because leaves are rougher than the flat plates for which the above expressions were obtained. It will be assumed therefore that

$$r_H \simeq r_v = r = \frac{0.9}{U} (Re)^{1/2} \qquad (29)$$

: for cereals the average width of the leaves is assumed to be 0.01m, leading to the expression

$$r = 23/U^{1/2} \quad sm^{-1} \tag{30}$$

The total surface area of leaves within the ith layer is 2xLAI(i) and so the effective boundary layer resistance of the foliage in this layer (the sum of the resistances of the separate leaf surfaces in parallel) is

$$r_i = 11.5/(U_i^{1/2} \times LAI(i)) \tag{31}$$

At the soil surface the boundary layer resistance r_n is determined from Eq (29), using for ℓ the typical size of clods of soil, assumed to be ~ 0.05 m, leading to

$$r_n \simeq 65/U^{1/2} \quad sm^{-1} \tag{32}$$

: U is assigned here the value of wind speed at the middle of the bottom layer.

3.8 Wind profile in canopy Wind speed decreases roughly exponentially with decreasing height within the upper part of the canopy:

$$U(z) = U(h)\exp(-q(1-z/h)) \tag{33}$$

(e.g. Denmead 1976): a coefficient values $q \simeq 2.5$ is assumed. In the lower part of a pasture canopy (say below $z = 0.4h$) wind speed probably begins to decrease more rapidly as the surface is approached. The following representation of this part of the profile in pasture-like canopies is adopted:

$$U(z) = U(0.4h)(1-2.5z/h)^j \qquad (z<0.4h) \tag{34}$$

where j is assigned the value of 3/2. A similar behaviour of wind in very immature cereal canopies to that given by Eq (34) is probably to be expected, but in more mature cereal canopies where leaf area density is small near the surface the relation (33) may be assumed to hold down to near the ground surface.

3.9 R_n This resistance is

$$R_n = \int_{z'}^{\frac{h}{2(n-1)}} (1/K(z))\,dz \tag{35}$$

where

$$z' = r_n \nu \simeq 10^{-3}/U^{1/2} \tag{36}$$

This treatment assumes that all heights above the surface are specified as if the clods had negligible dimension so that z' is the laminar boundary layer thickness at the soil surface. A rigorous specification of $K(z)$ near the bottom of the canopy is impossible, but on the assumption just given, and provided $(n-1)$ is not large (say ≥ 8) then a linear interpolation of $K(z)$ from its value given by Eq (22) to zero at the surface should not introduce

unacceptably large errors. Thus

$$K(z) = K\left(\frac{h}{2(n-1)}\right)\left[z/\frac{h}{2(n-1)}\right] \qquad (37)$$

and hence

$$R_n = \frac{1}{K(h/2(n-1))} \cdot \frac{h}{2(n-1)} \cdot \ln\left(\frac{1000\,h\,U^{1/2}}{2(n-1)}\right) \qquad (38)$$

In practice the clod size is such that on average the top of the laminar boundary above each clod will be close to the centre of the bottom layer. In this case R_n will be negligible: the model assumes it to be zero.

3.10 Layer stomatal resistances The response of stomatal resistance to temperature is ignored. There is likely to be a response to specific humidity deficit in the canopy but this is not included readily in the model because of an almost complete lack of published data on this response for grass and field crops. Watts (1977a) notes that stomatal conductances of Sitka spruce needles show a nearly linear decrease with increasing specific humidity deficit. Similar responses have been observed for other tree species. However in the case of sugar beet, when the leaf anatomy differs from spruce in having large numbers of water-conducting vessels very close to the guard cells of the stomata, the response of stomatal conductance to humidity deficit is apparently much reduced (Watts 1977b). Direct evidence on the response for grass or cereals is lacking. Many studies on field crops have indicated canopy resistances increasing with time during the day. However it has not always been clear whether this behaviour was solely the result of large negative soil water potentials (or of increasingly negative leaf water potential) or whether it was caused at least partly by an increase of specific humidity deficit from morning to afternoon producing partial stomatal closure. The model assumes at present that stomatal resistances are independent of the humidity deficit. The effects of light on stomatal opening are better known. Stomatal resistances decrease rapidly at first with increasing light intensity but then approach a nearly constant minimum value, reached with incident solar radiation around 500 Wm^{-2} (Monteith et al 1965). The cuticular value (stomata closed) for a single epidermis of wheat is around 5000 sm^{-1} (Denmead 1976) and this is used in the model at night. Values for fully-open stomata of sugar-beet and potatoes (which have amphistomatous leaves) have been measured by Brown (1976) at about 100 sm^{-1}, although Brown also quotes higher values from other investigations: both types of plants have substantially more stomata on the lower surfaces of leaves than on the upper surfaces and the quoted resistances are average values presumably. The minimum stomatal resistances of barley leaves (amphistomatous) are about 120 sm^{-1} for either cuticle (Monteith et al 1965). An average value of 120 sm^{-1} is assumed in the model and this is likely to be a fairly satisfactory approximation for cereals, potatoes and sugar-beet. The variation of stomatal resistance with soil moisture deficit is not included in the model at present.

The layer stomatal resistance is given by

$$r_{si} = r_s / (2 \times LAI(i)) \qquad (39)$$

where r_s is the leaf stomatal resistance which is given approximately by (Monteith et al 1965).

$$r_s = 120\ sm^{-1} \quad (S(i) \geqslant 500\,W\,m^{-2})$$

$$= 10^4\left(2 + 1.01\,S(i) - .006091(S(i))^2 + .00001535(S(i))^3 - .0000000131\,7(S(i))^4\right)^{-1} \quad (0 < S(i) < 500) \qquad (40)$$

where $S(i)$ is the downward solar radiation in the ith layer. $S(i)$ is assumed to be related with sufficient accuracy to the value $S(0)$ at the top of the canopy by

$$S(i) = S(0) \exp\left(-k' \sum_{p=1}^{i} LAI(p)\right) \qquad (41)$$

where k' is given by Eq (9). From Eq (1) one may write

$$S(0) = S F_1 \sin\theta \qquad (42)$$

and so

$$S(i) = S F_1 \sin\theta \exp\left(-k' \sum_{p=1}^{i} LAI(p)\right) \qquad (43)$$

3.11 r_{sn} The derivation of a simple empirical treatment which estimates evaporation from the soil surface is beset with difficulties. When evaporative demand is high (as can be the case when crop cover is sparse) any water in the upper soil layers is lost rapidly at first, but the rate of evaporation then decreases sharply. With lower evaporative demand the drying of the soil may proceed at close to the potential rate until a total water extraction larger than that occurring in a rapid drying phase has taken place (Penman 1963). An adequate model of soil moisture evaporation for a dense canopy (for which evaporation from the soil is small compared to transpiration) may be to assume that all the available energy is partitioned into sensible heat if the soil surface is dry (r_{sn} very large) or into latent heat if fully wetted ($r_{sn} \sim 0$). The present canopy model uses these assumptions, with the transition between "dry" and "wet" assigned arbitrarily to a soil moisture deficit of 10 mm in the surface layers. A more elaborate treatment of evaporation is necessary if crop cover is sparse but is not yet developed for this canopy model.

3.12 Soil heat flux Results from Monteith (1958) suggest that under a bare soil surface the heat flux during the day is about 40% of the net radiation. His daytime results under wheat, grass and potatoes are consistent with an approximate relation

$$G = 0.4\, RADN(0) \left(1 + 0.4 \sum_{p=1}^{n-1} LAI(p)\right)^{-1} \qquad (44)$$

which is used in the present model. At night when the soil is dry an average value for G is about 50% of the net radiation. With wet soils the position is less clear because of considerable scatter in the results, but a rough fit is obtained if G is assumed to be 80% of net radiation (Utaaker 1966) (this last result was for grass cover, but Monteith (1958) measured some values in excess of 100% of net radiation for wheat and potatoes: however his data were sums over the nighttime period which introduced some bias because "nighttime" (negative) soil heat fluxes occur for a longer period than negative net radiation).

There are conflicting results on the behaviour of G during the hours around sunrise and sunset (e.g. Roach 1955, Monteith 1958, Utaaker 1966, Smith and Hunt 1978). By placing more reliance on the results of Smith and Hunt (who corrected measured soil heat fluxes to those expected at the soil surface) and Monteith (who measured the fluxes at only small soil depths (0.5 cm to 3 cm below the surface) one obtains the approximations

"nighttime" (i.e. sunset to sunrise) : use values given above for nighttime.

"daytime" (sunrise to sunset) : sunrise to sunrise + 2 hours, put $G = 0$
: after sunrise + 2 hours, use eq (44) unless time is before midday and $RADN(0) < 0$, when $G = 0$, or if after midday and $RADN(0) < 0$, when nighttime values for G are used.

3.13 Derivation of wind speed etc at top of canopy The specific humidity at screen level is obtained from the approximation

$$QSCR = 0.00062 \exp\left(19.0785 - 4098.03/(TD + 237.3)\right) \qquad (45)$$

where TD is the dewpoint in the screen. The diabatic profile of wind is represented by the approximation

$$U(z) = \frac{u_*}{k}\left(\ln\left(\frac{z-d}{z_0}\right) - \psi_M\left(\frac{z-d}{L}\right)\right) \qquad (46)$$

(e.g. Thompson 1978) where

u_* = friction velocity

k = 0.4 (von Karman's constant)

d = displacement height ($\simeq 0.63h$)

z_0 = roughness length ($\simeq 0.1h$).

$$L = \frac{-u_*^3 (T+273)\rho c_p}{kg(H+0.07E)} \simeq \frac{-u_*^3 . 90270}{H+0.07E} \quad (T=15^\circ C) \qquad (47)$$

In unstable conditions

$$\psi_M\left(\frac{z-d}{L}\right) = 2\ln\left(\frac{1+y}{2}\right) + \ln\left(\frac{1+y^2}{2}\right) - 2\tan^{-1} y + \pi/2 \qquad (48)$$

where

$$y = \left(1 - 16\left(\frac{z-d}{L}\right)\right)^{1/4} \qquad (49)$$

In stable conditions

$$\psi_M\left(\frac{z-d}{L}\right) = -5\left(\frac{z-d-z_0}{L}\right) \qquad (50)$$

Profiles of potential temperature and specific humidity in unstable conditions are approximated by

$$\frac{\theta(z)-\theta(0)}{T_*} = \frac{q(z)-q(0)}{q_*} = \frac{1}{k}\left[\ln\left((1-y_1)/(1+y_1)\right)\right]_{z_{T,q}}^{z-d} \qquad (51)$$

where

$$y_1 = y^2 \tag{52}$$

$$T_* = -H/\rho c_p u_* \tag{53}$$

$$q_* = -E/\rho u_* \tag{54}$$

$$z_{T,q} \simeq 0.2\, z_0 \tag{55}$$

In stable conditions Eq (51) becomes

$$\frac{\theta(z)-\theta(0)}{T_*} = \frac{q(z)-q(0)}{q_*} = \frac{1}{k}\left[\ln\left(\frac{z-d}{z_{T,q}}\right) + 5\left(\frac{z-d-z_{T,q}}{L}\right)\right] \tag{56}$$

H and E (the upward fluxes of sensible heat and water vapour at the top of the canopy) are not known initially and so the equations cannot be solved in one step because L is not determinate. The procedure adopted assumes a Brown ratio of unity initially, and the value of u_* for neutral conditions (obtained by putting $\psi_m = 0$ in Eq (46)). The corresponding estimates for $U(h)$, $\theta(h)$ and $q(h)$ are used in the solution of the $3n$ layer resistance equations (see § 3.14) from which are obtained new values for H and E : final values are obtained by successive approximations using re-iterations of this procedure. $U(h)$, $T(h)$ and $q(h)$ are then derived readily from the formulae.

The diffusion coefficient for heat and water vapour at the top of the canopy is obtained from the usual relation (e.g. Dyer and Hicks 1970, Webb 1970)

$$K(h) = k u_* (h-d)\, y_1 \qquad (L<0)$$

$$= k u_* (h-d) \Big/ \left(1 + 5\left(\frac{h-d}{L}\right)\right) \qquad (L>0) \tag{57}$$

3.14 Solution of resistance equations Eq (13), (17) and (21) may be combined as a matrix of $3n$ equations with $3n$ unknowns, represented by

$$\left.\begin{array}{l} \vdots \\ O(H_1 \to H_{i-1}) + H_i + O(H_{i+1} \to H_n) + O(E_1 \to E_{i-1}) \\ \quad + \lambda E_i + O(E_{i+1} \to E_n) + O(\Theta_1 \to \Theta_n) \\ \qquad = RADN(i-1) - RADN(i) \\ \vdots \end{array}\right\}$$

$$
\left.
\begin{aligned}
& H_1 R_1 + \cdots + H_i \left(\sum_{p=1}^{i} R_p + r_i \right) + \cdots + H_n \left(\sum_{p=1}^{i} R_p \right) \\
& + O(E_1 \rightarrow E_n) + O(\Theta_1 \rightarrow \Theta_{i-1}) - \rho c_p \Theta_i + O(\Theta_{i+1} \rightarrow \Theta_n) \\
& \qquad = 0 \\
& \vdots \\
& O(H_1 \rightarrow H_n) + E_1 R_1 + \cdots + E_i \left(\sum_{p=1}^{i} R_p + r_{si} + r_i \right) + \cdots + \\
& E_n \sum_{p=1}^{i} R_p + O(\Theta_1 \rightarrow \Theta_{i-1}) - \rho \Delta' \Theta_i + O(\Theta_{i+1} \rightarrow \Theta_n) \\
& \qquad = \rho \delta q \\
& \vdots
\end{aligned}
\right\} \quad (58)
$$

A standard IBM library routine is used to solve the equations.

3.15 Interception and evaporation of rain The maximum interception of each layer is assumed to be

$$\text{MAXINT}(i) = r.\ \text{LAI}(i) \qquad (59)$$

where r depends (strictly) on the type of crop: the (constant) value used at present in the model is 0.2 Kg m^{-2} ($\equiv$ 0.2 mm rainfall) which is consistent with results obtained for grass by Couturier and Ripley (1973). Other assumptions are:

(a) Rain wets layers at rates proportional to leaf area index of each layer.

(b) Only part of the rainfall may be effective in wetting the canopy. For example Couturier and Ripley (1973) found that the approach to full wetting for grass was roughly exponential. The leaf area index of the canopy they studied (both living and dead leaves) was about 5; this canopy intercepted most of the incident rain until about one third of the storage capacity was reached. If it is assumed during this stage of wetting that each layer intercepts a fraction $f.\ \text{LAI}(i)$ of the rain falling on the layer, then for a 5-layer canopy where $\text{LAI}(i) = 1.0$ the fraction of rain intercepted by the whole canopy is $(1 - (1-f)^5)$. On this basis the minimum value which f can take is certainly greater than 0.2. The present model assumes that f is 0.4 until half the interception capacity is reached, when it decreases to 0.15. These assumptions are written more formally as

$$
\left.
\begin{aligned}
\text{INT}(i) &= 0.4\ R(i).\ \text{LAI}(i) && (\text{INT}(i) < 0.5\ \text{MAXINT}(i)) \\
\text{INT}(i) &= 0.15\ R(i).\ \text{LAI}(i) && (\text{INT}(i) > 0.5\ \text{MAXINT}(i)) \\
\text{INT}(i) &= 0 && (\text{INT}(i) = \text{MAXINT}(i))
\end{aligned}
\right\} \quad (60)
$$

$$R(i) = R - \sum_{p=1}^{i-1} INT(p) \qquad (61)$$

where

$INT(i)$ = amount of rain intercepted by ith layer

R = amount of rain

$R(i)$ = amount of rain reaching ith layer

$INIT(i)$ = storage of water in ith layer at start of rain

(c) Assuming rainfall data are available hourly: canopy is at capacity at the start of a simulation run if rainfall in previous hour is not zero.

(d) Canopy is dry at start of simulation if rainfall in previous hour is zero.

(e) Rainfall for any hour is divided into 6 equal amounts, each assumed to fall instantaneously at the start of each 10-minute period.

(f) If any canopy layer is wet at the start of any 10-minute period then r_s for that layer is made zero. r_s attains its normal value at the start of the first 10-minute period following that in which the water finally evaporated.

(g) Storage in a layer at the end of each 10-minute period is obtained by subtracting evaporation during the period from the sum of initial water storage and rain intercepted in the period: the resulting value is constrained to lie within the limits $0 < \text{storage} < MAXINT(i)$.

3.16 Formation and evaporation of dew Evaporation of dew is treated in the same way as evaporation of intercepted rain, by following the water balance over successive 10-minute periods.

The formation of dew is harder to treat because r_s should strictly be made equal to zero as soon as a negative net water vapour flux is calculated for any layer. The model comprises by putting $r_s = 0$ at the start of the 10-minute period immediately following that in which the negative water vapour flux is predicted for a layer: the zero value is retained until the first 10-minute period following that in which the net flux again becomes positive.

3.17 Computational procedure In § 3.13 it was pointed out that final solutions of the resistance equations (58) cannot be obtained until wind speed, temperature and specific humidity at the top of the canopy are determined. This involves calculating L, and since this cannot be done until sensible and latent heat fluxes from the canopy are known an iterative procedure is required. A rough value for L is obtained by first assuming near-neutral (logarithmic) profiles of wind, temperature and specific humidity above the canopy and then, using the resulting estimates of wind etc at the canopy top deriving H and E at canopy top using the canopy model; L may then be determined by iteration of Eq (46)-(56). New values of the variables at the canopy top are calculated and used in the canopy model which then produces the final solutions after 12 iterations.

A difficulty arises if the temperature and humidity data obtained at screen level over short grass are assumed to represent conditions at the same height above ground when the underlying vegetation is much taller. Included in the calculations therefore is a conversion of screen data to a reference height of 10 m; it is assumed that conditions at this height will vary insignificantly with variations in the type of vegetation covering the underlying ground, provided $h \ll 10$ m (say $0 < h < 1$ m).

4. Some results for a dry canopy The model was tested against some data obtained within and above wheat canopies by Penman and Long (1960) during June 1955 and June 1956. The earlier data were 9 sets of average values of wind, temperature and humidity obtained during periods between 1 and 2 hours long on 4 and 5 June. The data used for input to the model were temperatures and humidities measured above the crop and interpolated to screen level and 10 m wind speeds estimated from those measured at 2 m. Data obtained in two of the periods in which dew was forming were not included in the tests. The crop area had been drilled in plots with different seed densities and the model was run to simulate profiles above and within two of the plots (i) normal drilling density, crop height 0.22 m, LAI assumed to be 1.8 (ii) high density drilling, crop height 0.31 m, LAI assumed to be 3.3. Unfortunately the above-canopy data were obtained over plot (i) only (at 1 m and 2 m) and may have been somewhat different over plot (ii). The soil was wet following recent substantial rainfall. Amounts of cloud were not known in any detail but conditions appeared to be overcast initially. Cloud broke up during the first day and amounts of cloud during the remainder of the period were probably small. Overcast conditions were assumed for the first two periods and quarter-cover for the next. Thereafter the cloud amount was assumed to be negligible. Model outputs are compared with measured temperatures at 12.5 and 25 cm are with humidities at 12.5 cm in Figure 2(a). During the first two periods the measured profiles departed only slightly from isothermal and although the simulations did not match them very closely the differences were typically only about 0.2 to 0.3 deg C. In the third period the calculated temperatures were much too large (by about 2 deg C), indicating almost certainly that the amount of radiation reaching the surface had been overestimated and that there was, presumably, a significant cloud cover remaining at this time. Results from the remaining 4 cases were almost certainly for occasions with little cloud and therefore more reliable for comparisons with the model results. In each case the simulations of the dense crop were cooler than the measured values, by up to 2 deg C. Results from the sparser crop were closer though even here the average measured relative humidity at 12.5 cm was about 6% less than calculated (a similar difference occurred for the dense crop). Some of the disparity between measured and simulated values for the denser crop may have been due to the necessary use of temperature data measured above the sparser crop as input to the model. Also the fact that crops usually appear to suffer premature stomatal closure in the late afternoon even when freely supplied with water (not taken account of in the model) would have produced crop temperatures higher than those simulated for 1900Z on 6 June.

The Penman-Monteith equation was applied to the data for 1200Z on 6 June and gave an upward water vapour flux 5% less than the simulated one for the dense crop and an upward heat flux nearly 50% larger: the value used for bulk stomatal resistance was 20 sm^{-1}, which was close to that obtained from the model leaf stomatal resistances in parallel. The evidence is therefore that the model underestimates canopy temperature and hence overestimates humidity by partitioning too much of the available energy into the latent heat flux.

5. Results for a wet canopy Figure 2(b) show results for the two periods in which dew was forming. Disagreement between model outputs and measured data is very large. However winds were very light at 2 m and in these conditions it is uncertain whether the flow above the crop was fully turbulent. If it had not been the temperature would have fallen well below model values in the canopy. The rate of dew formation indicated by the model was about 0.05 Kg m^{-2} hr^{-1} which compares well with the value of 0.06 Kg m^{-2} hr^{-1} suggested by Penman and Long.

6. Concluding remarks These first results from the model have been disappointing although they do not necessarily indicate that the model is quite unsuited in its present form to the estimation of water loss from drier canopies such as cut grass; a modified form of the model is being constructed for this application. The results suggest that the model needs refining before it can begin to be applied with success to the simulation of the drying of wetted canopies, for which it was developed originally. It is hoped to carry out further tests of the model using more precise data from taller crops before attempting any major modifications.

Any comments or suggestions on this paper should be referred to the author.

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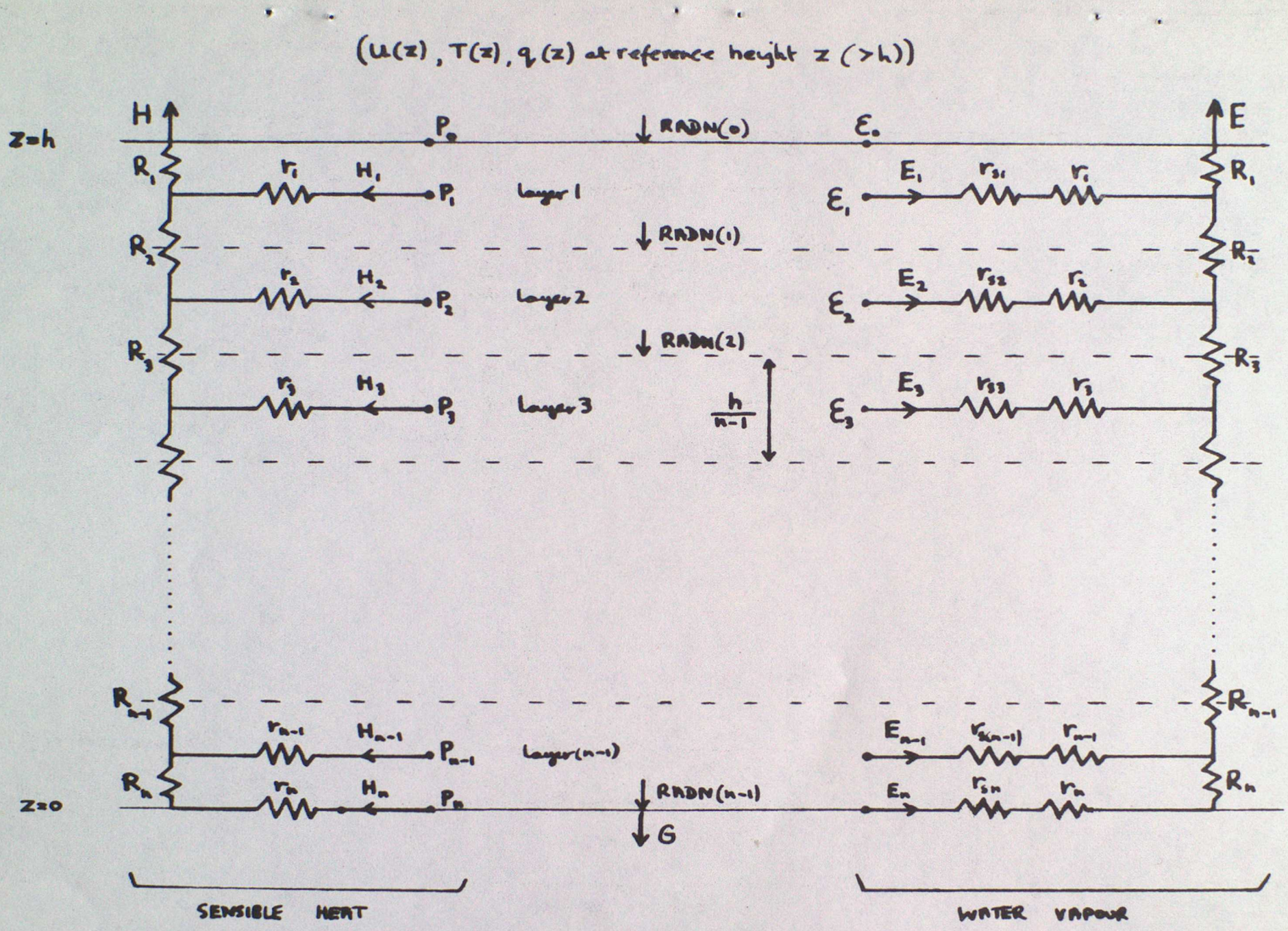

Figure 1 Outline of canopy model

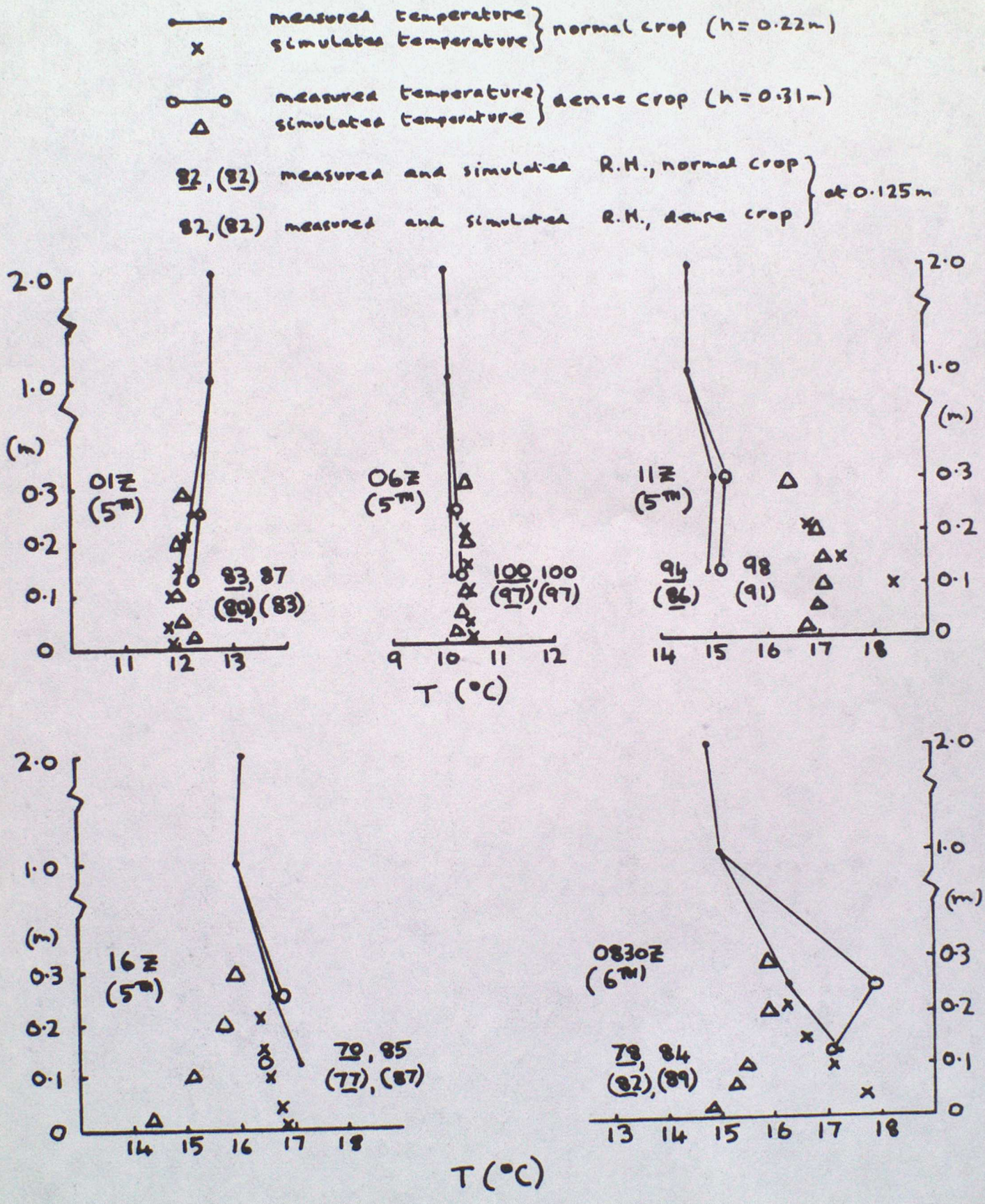

Figure 2a. Measured and simulated profiles over a dry canopy

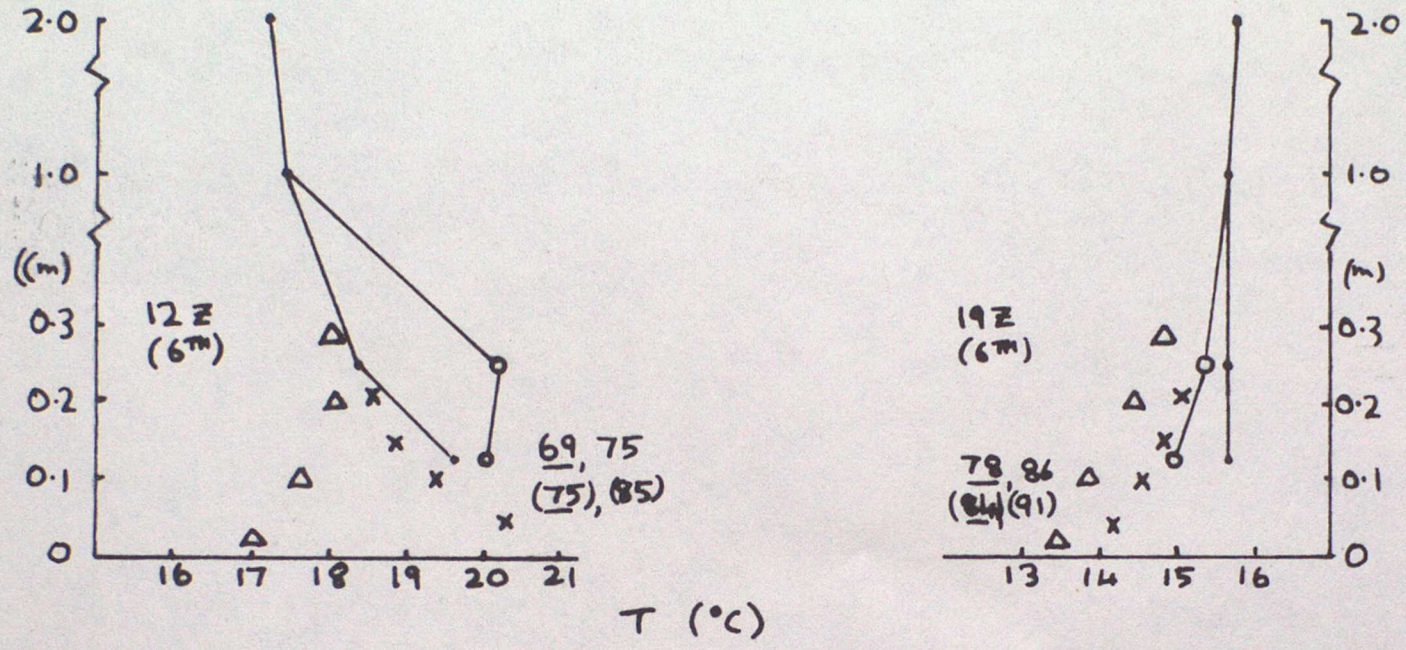

Figure 2a. (Continued)

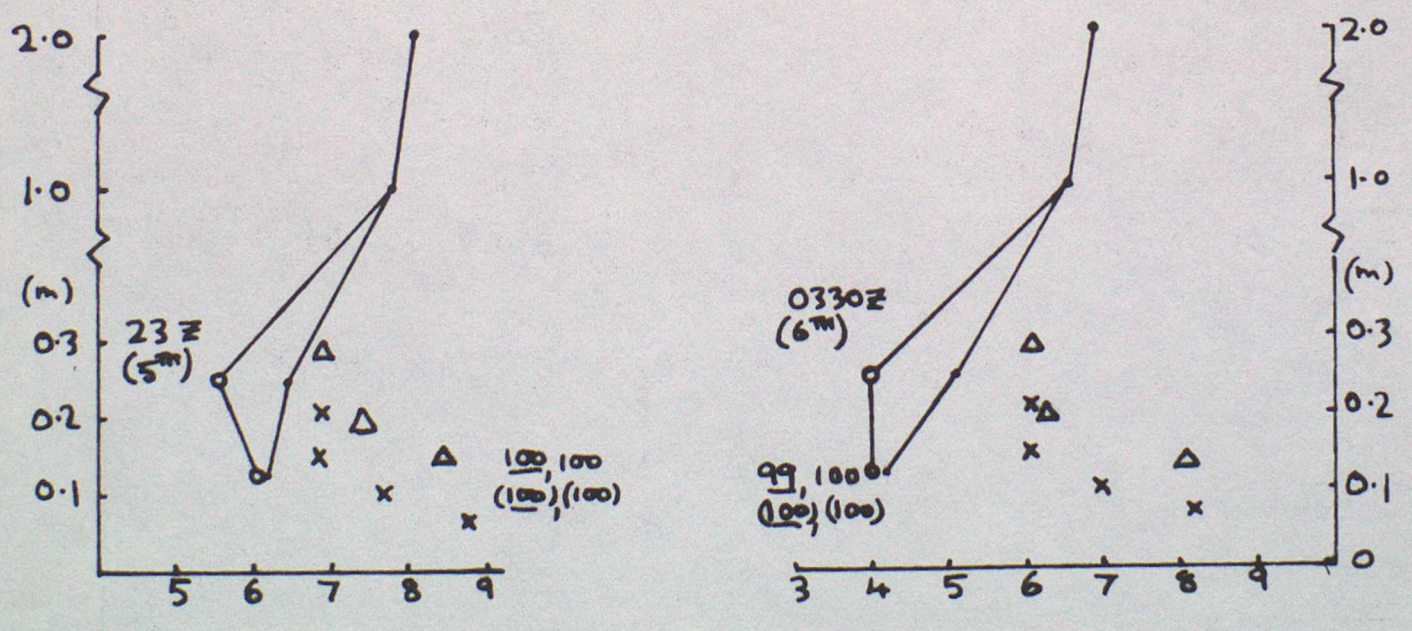

Figure 2b. Measured and simulated profiles for a wet canopy